A REVIEW OF FEA TECHNOLOGY ISSUES CONFRONTING THE POWER INDUSTRY

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SUMMARY

This paper summarises the current state of practice and the state of art in the use of the finite element (FE) technology in the Power and Pressure Systems industry sector. The industrial requirements, needs and barriers have been reviewed along with the research work required in future. A general view is that there is a high usage of FE technology in conducting design sensitivity studies and in predicting fatigue/fracture life. FE technology is being developed to take account of issues like aging and fracture related failures at joints which were not adequately covered in the original design codes. Rapid progress is being made in multi-physics areas like simulation of residual stresses and fluid/structure interaction. There is a need to establish a number of high quality benchmarks covering various aspects of pressure vessel analysis which can be used for validation and verification purposes. It is hoped that with further uptake of the FE technology, the Design by Analysis approach will mature and will be accepted by the industry standard design codes and regulatory bodies.

1: INTRODUCTION

This paper summarises the current state of practice and the state of art in the use of the finite element (FE) technology in the Power and Pressure Systems industry sector. The business drivers (industrial requirements) and needs have also been reviewed along with the research work required in future. The findings are based on the survey conducted by the FENET project, various FENET Workshops held since the start of the FENET project, the European Pressure Directive and the observations made by the authors at other technical seminars/conferences organised by the IMechE, INucE, NAFEMS, IAEA, British Society of Strain Measurement (BSSM), ASRANET and INTUITION.

2: STATE OF PRACTICE

State of Practise refers to the degree of uptake of a technology by industry - it is in effect a reflection of the maturity of the industrial usage. The survey conducted by the FENET project indicated that in the Power and Pressure industry sector, FE techniques are mostly used in the design, analysis and assessment of the following items:-

- Vessels, tanks and containers
- Pressure equipment for nuclear and alternative power generation
- High Pressure and Low Pressure piping systems

3: STATE OF THE ART

State of the Art refers to the degree to which a technology has been developed to meet a perceived need. Technology Readiness Level (TRL) is a measure of this. TRL gives an idea of the maturity of a given method or tool. The definition of TRL has been taken from NASA [4]. The use of the FEA technology in the power and pressure vessel industry has matured over a number of years. Many new and existing designs have been substantiated by FEA. A general view is that in conducting design sensitivity studies and in predicting fatigue/fracture life the TRL is judged to be high. In multi-physics areas like simulation of residual stresses and fluid/structure interaction the TRL level is 4. The lowest TRL is in simulation of accident scenarios which involves computational modelling of combustion. A summary of the TRL for the main issues is presented in Figure 1.

Size of the circle indicates priority level : Largest circle = Highest priority

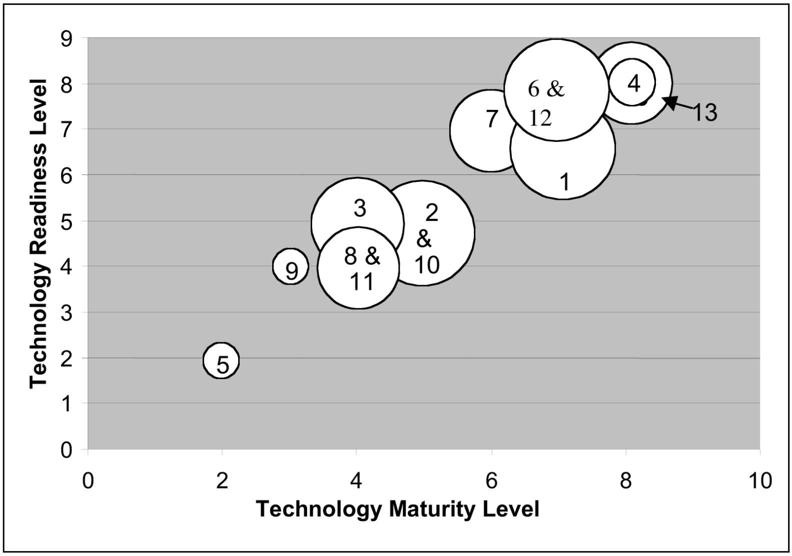

Figure 1: Maturity and Readiness Levels of FEA Technology in Power & Pressure Systems Industry

1 Fatigue and Fracture
2 Aging/ Stress Corrosion Cracking /Embrittlement
3 Accident Scenarios: Impact
4 Accident Scenarios: Fire Thermal Deformation
5 Accident Scenarios: Fire Combustion
6 Sensitivity Studies
7 Structural Reliability Methods: Numerical
8 Structural Reliability Methods: FORM/SORM
9 Fluid/Structure Interaction
10 Residual Weld Stresses
11 Extreme Wind Loading
12 Validation and Verification/ Benchmarks
13 QA Systems/ Accreditation of analysts

4: AREAS FOR RESEARCH

The Survey and the Workshops identified the following future requirements:-

- Post-processing of the FE results to demonstrate compliance with design codes
- Going beyond the original design basis
- Move towards probabilistic analysis
- Fracture Mechanics for life extension and repair
- Analysis of welded and bolted joints
- Awareness of Design by Analysis (DBA) manuals

The aforementioned issues define the current requirement of the power and pressure vessel industry. These are directly related to the needs of the industry which are discussed in more detail in section 5. Some researchers have developed methods to solve these by use of FEA. There is a need to disseminate the latest research and development in these areas to further the level of FEA usage in the industry. A summary of the requirements with priority levels is presented in Figure 1.

5: BUSINESS DRIVERS AND INDUSTRY NEEDS

The main reasons for the use of the FE technology in the Power and Pressure industry sector are:-

- Design by Analysis
  - Customisation of the analysis process
  - Implementation of the new European Pressure Directive
- Compliance with design codes
- Predicting limit loads
- Asset management and life extension
- On line monitoring

Whilst the use of FEA in the power and pressure vessel industry is wide spread there still remain a number of barriers in further enhancing the role of FEA. These issues are:-

- How to satisfy the regulatory bodies
- Modelling issues (Bolts, seals and connections)
- Validation and verification
- Better material data
- Promote and improve the Design by Analysis manual
- Use of probabilistic methods
- Life extension- Fracture mechanics
- Multi-physics situations – sequential testing e.g. impact followed by fire
- FE and the Design Codes - Integration of FE in the design process

Further details are presented in the following sections.

6: REGULATORY BODIES

FEA is regularly used in the power and pressure industry sector to substantiate a design. An analysis is often followed by detailed assessment of the results to prove the structural integrity of the vessel for safety requirements. Such details are required by regulatory bodies and/or insurance companies to grant an operating licence. The main issue here is that such regulatory bodies may not accept a case based on FEA alone and may demand calculations based on certain design codes. Currently, there are no pressure vessel design codes which give any guidance on design by FEA. A proposed draft of Design by Analysis (DBA) manual [2] exists which is discussed later. What is required is a clear guidance from regulatory bodies which specify the acceptance criteria for design substantiation by FEA. It is recognised that most regulatory bodies would not issue such clear guidance. In the absence of appropriate British/International standards then perhaps an 'industry standard' may be a good initial step. The Atomic Energy Code of Practice series has been produced by the Transport Container Standardisation Committee (TCSC) in the UK. They provide useful practical guidance for the analysis of specific components and are an eclectic mix of standards. Regulators do not go as far as endorsing these documents but they do review them and look upon them favourably. The TCSC is currently considering producing a code of practice on 'FEA of Radioactive Material Transport Packages'. Some of these documents are now referenced by the IAEA Advisory material (Ref 10).

7: MODELLING ISSUES

Main components of a typical pressure vessel are: cylindrical section, ends, supports and nozzles or penetrations. Modelling of these features is well within the capability of a number of commercially available FE codes. However, modelling of the following features is not straight forward and requires specialist knowledge:-

- Bolts
- Seals/gaskets
- Welded joints

Bolts are discrete structural elements connecting axisymmetric shell or solid structural components like flanges. Furthermore, they may be pre-tensioned. Seals and gaskets, if present, are essential to prove the pressure retaining capacity of a vessel. Such components exhibit nonlinear behaviour and their thickness Vs pressure characteristics may alter if load is cycled. Fillet or butt welded joints are regularly used in fabrication of a pressure vessel, but they are hardly ever modelled in an explicit manner in a FE model. The geometry of a welded joint may not be known and furthermore, there may be residual stresses which can not be modelled. This can be taken as a research topic for the 'multi-physics'. The issue of welded joints modelling has been picked up by the Education and Dissemination co-ordinators and after a workshop a report on Procedural Benchmarks for Common Fabrication Detail (Ref 7) has been issued.

8: VALIDATION AND VERIFICATION

If FEA is to be used to substantiate pressure vessel designs, then the validation and verification of the FE models and the analysis results is required to be reported and recorded. Whilst verification of the computer code is often provided by the code developer, validation of an FE model remains the responsibility of the analyst and is carried out by:-

- comparison of the results with measured test data
- comparison of the results with values obtained by independent means (another FE code or hand calculations)

There is a need to have a number of high quality benchmarks covering various aspects of pressure vessel analysis. These benchmarks can be used for validation and verification purposes. However, full validation and verification may not be required if a FE model was sufficiently conservative and demonstrated large enough margins on the assessment criteria. In such cases, the concept of 'fitness for purpose' is used as a subset of full validation.

9: DESIGN BY ANALYSIS (DBA)

As mentioned in Ref [1], there are two basic approaches to the design of engineering components and structures: design by rule and design by analysis. In the design by rule approach, rules and limitations set by a design standard are adhered to. The design by analysis approach requires either analytical or computational effort to predict stress levels and this is where the FEA is often used.

Engineers need to be made aware of the problems in using FE analysis in conjunction with design codes. If no relevant design code is available, the engineer may have to rely entirely on FE analysis and engineering judgement to substantiate the design. The basic principles used in design codes should be understood if FEA results are to be used to demonstartedemonstrate code compliance. It should be noted that the methodology and nomenclature of old design codes are different from those used in numerical techniques like FEA. Since FEA can produce a lot of detailed stress information, it is important to appreciate the importance of various classes of stresses. The catagorisation of stresses into primary, secondary and peak done by some design codes has to be applied to the stresses obtained from FEA. The numerical procedures used to post-process FEA results must not violate the principles set by the design codes.

The Design-by-Analysis Manual [2] has recently been published which provides guidelines for DBA to typical pressure vessel structures under a variety of loading conditions, focussing on aspects that would accelerate the uptake of FEA in the power and pressure vessel industry. The following actions need to be taken to promote the use of FEA through DBA:-

- Promote the DBA manual [2]
- Further improvements to the DBA manual by including the use of 3D solid elements
- Standardise a method to catagorise and linearise stresses obtained from FEA
- Inclusion of DBA in other guideline documents like the IGE/TD12 which is being revised by the Inst. Of Gas Engineers in the UK

- Link with other projects like the Virtual Institute on Design by Analysis of Pressurised Equipment (VIDAPE)
- Include nonlinear analysis methodology in the DBA
- Include high temperature design guidelines in the DBA
- Influence the FE code developers to provide facilities to catagorise and linearise stresses in their post-processing packages
- Accreditation of analysts

10: USE OF PROBABILISTIC METHODS

The whole process of the finite element analysis is based on approximation. It is important to understand the various reasons for the difference between the real structural behaviour and the FE results. Meanings of the terms ‘uncertainty’, ‘errors’ and ‘mistakes’ need to be clarified to ensure consistency when reviewing accuracy of FE results.

‘Uncertainty’ exists in a parameter when it is not possible to define its value exactly. Uncertainties associated with an engineering problem can be divided into two groups: aleatory (natural) and epistemic (knowledge). Aleatory uncertainty is natural or inherent randomness which cannot be reduced or eliminated but can be taken into account by performing sensitivity studies. Epistemic uncertainty is related to lack of knowledge about exact dimensions, loads, imperfections etc. and can be reduced within certain limits by collecting more accurate information. ‘Error’ accounts for all other differences in behaviour between the real structure and the analysis results. The difference due to ‘uncertainty’ in the physical description of the real structure should be distinguished from ‘error’.

The term ‘accuracy’ is used most commonly to refer to the accuracy with which the model represents the real structure. Loss of ‘accuracy’ arises from the simplification of a real problem to a mathematical model.

Loss of accuracy caused by the process of approximating a continuum with finite elements is referred to as ‘discretisation error’, particularly in the context of automatic mesh refinement. This form of error does not mean that the analysis is wrong.

FE programs issue warning and error messages in the diagnostics. In this context error usually means ‘mistake’. Most are fatal and cause the analysis to be aborted. Warnings are to draw attention to input commands which do not cause the run to fail, but are unusual and may not be as intended. Apart from these warnings, the program can only check that the problem described by the input data is soluble. It cannot check that it represents the problem that the user intended to solve, or ought to have solved.
‘Variability’, ‘uncertainty’ and ‘accuracy’ are now taken into account by use of partial safety factors which are used in the new limit state design codes. These factors are calibrated to achieve a certain target reliability in the design. In the pressure vessel industry, these factors have to be justified by probabilistic investigations which may include Monte Carlo or other structural reliability methods.

A joint meeting of FENET with the ASRANET and the Institution of Structural Engineers was held on 30 June 2003 [5] where the Best Practice Guidance for the use of risk and reliability methods in structural integrity management was presented. In 2004, ASRANET launched an exclusive journal database ASJOUDAT (ASranet JOUrnal DATabase) for online search of technical papers on reliability.

11: LIFE EXTENSION - FRACTURE MECHANICS

A recently published British Standard BS7910 [3] provides guidance on assessing acceptability of flaws in metallic structures. This code supercedes PD6493 which has been extensively used in the power and pressure industry. Use of FEA with BS7910 is a powerful means of defining critical crack sizes and judging acceptability of various types of flaws in a typical pressure vessel. FEA already plays an important role in estimating stresses and performing fracture mechanics assessment. However, there is need to develop techniques to use FEA for dynamic fracture mechanics.

Whilst the FEA techniques are fully developed to predict stresses in pressure vessel and piping systems, their use in predicting life of the componets is restricted due to the lack of data to take account of aging, stress corrosion cracking (SCC) and embrittlement. The Technical Working Group meeting of the International Atomic Energy Agency [6] concluded that many aging related problems were not anticipated at the design stage. The design codes do not cover degradation like the SCC which effects the conventional engineering plants as well.

Most of the fracture related failures occur at joints particularly at the welded joints. Extracting stresses at a welded joint by performing FE analysis is a complex issue. The seminar held at I Mech E [8] shows that the technology to simulate the welding and Post Weld Heat Treatment (PWHT) to predict residual stresses is making rapid progress due to the high priority placed on it by the industrial users.

Recently, a wide ranging study of the generation of residual stresses during welding, their variation during service life under thermal and mechanical loading, and the effect of stress relaxation on creep damage in stainless steel has been conducted by the VORSAC (Variation Of Residual Stress in Aged Components) project [9]. The VORSAC project provided validated predictive methods for assessing the role of residual stress relaxation and creep damage on delayed reheat cracking. It also generated increased knowledge of the effectiveness of remedial methods including post-weld heat treatment and last pass heat-sink welding, and on the effect of service temperatures, load transients and constraint on stress variation during manufacture, heat treatment and service life. The comparison of predicted and measured residual stresses showed that the trends in residual stress distributions could be reasonably predicted using finite element analysis, and large differences only occurred in local stresses.

12: FE AND THE DESIGN CODES

Many engineering companies often have a contractual obligation to show that their design meets the requirements set down in the design code agreed between the supplier and the buyer. Depending on the component or the structure being designed, this can be one of the Eurocodes and/or British Standards like BS449 and BS5950 for steel structures, BS5500 (now PD 5500:2003) for pressure vessels, BS8110 for concrete structures or any of the industry standard accepted by professional bodies. This is where the problem begins. Whilst an analyst may have performed a very detailed analysis, he or she may not be able to utilise directly the results from the finite element analysis to show that the design meets the requirements set down in the design code. It is mainly because the finite element method was developed several years after the writing of many of the design codes, which only set out to avoid certain failure modes. Furthermore, the design codes rely on built in conservatism and their methodology and nomenclature are often different from those used in numerical methods such as finite elements. As discussed in Ref 1, the stresses obtained from FE analysis often have to be `linearised` and `catagorised'. As engineers, engaged in substantiation of designs, move closer to more sophisticated numerical analysis techniques, the gulf between the 'numerical analysis' and the 'design code assessment' seems to widen. It is essential that an engineer who is familiar with the design codes should also be fully conversant with the FE method and vice versa.

13: BARRIERS

Following are the main barriers or problems which have to be overcome to promote further uptake of FEA in the power and pressure vessel industry:-

- How to validate and verify the FEA results?
- How to satisfy the Regulators?
- How to increase awareness about the DBA manual?
- How empirical knowledge can be included in the FEA?
- FEA is <u>not mentioned</u> in most design codes/standards !

The Survey and the Workshops have identified two more issues which are seen as barriers in the use of FE technology in Europe:-

(i) Reliance on American codes

In the Nuclear sector there is wide spread reliance on the ASME codes where as the piping and the pressure equipment in the Oil and Gas sector mostly uses the API codes. Knowledge and expertise of these American codes is somewhat limited in Europe.

(ii) Gap between FE and the design code terminology

An analyst is often required to utilise directly the results from FE analysis to show that the design meets the requirements set down in the design code specified by the client or the safety authorities. The design codes rely on built in conservatism and their methodology and nomenclature are often different from those used in numerical methods such as finite elements. As discussed in Ref 1, the stresses obtained from FE analysis often have to be `linearised` and `catagorised'.

14: CONCLUSIONS

The FENET project has identified the major issues related to the uptake of FE technology in power and pressure systems industry. In some technology areas like the design sensitivity studies and fatigue/fracture assessment, the Technology Readiness Level and the state of practice is high. However, the Technology Readiness Level in multi-physics, particularly that related to simulation of welding to predict residual stresses was low but is making rapid progress due to the high priority placed on it by the industrial users.

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